# Revisiting pseudo-Dirac Neutrino scenario after recent solar neutrino data

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HIDDe$\nu$
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Asymmetry
Essential Asymmetries of Nature

# Solar Neutrino Oscillations

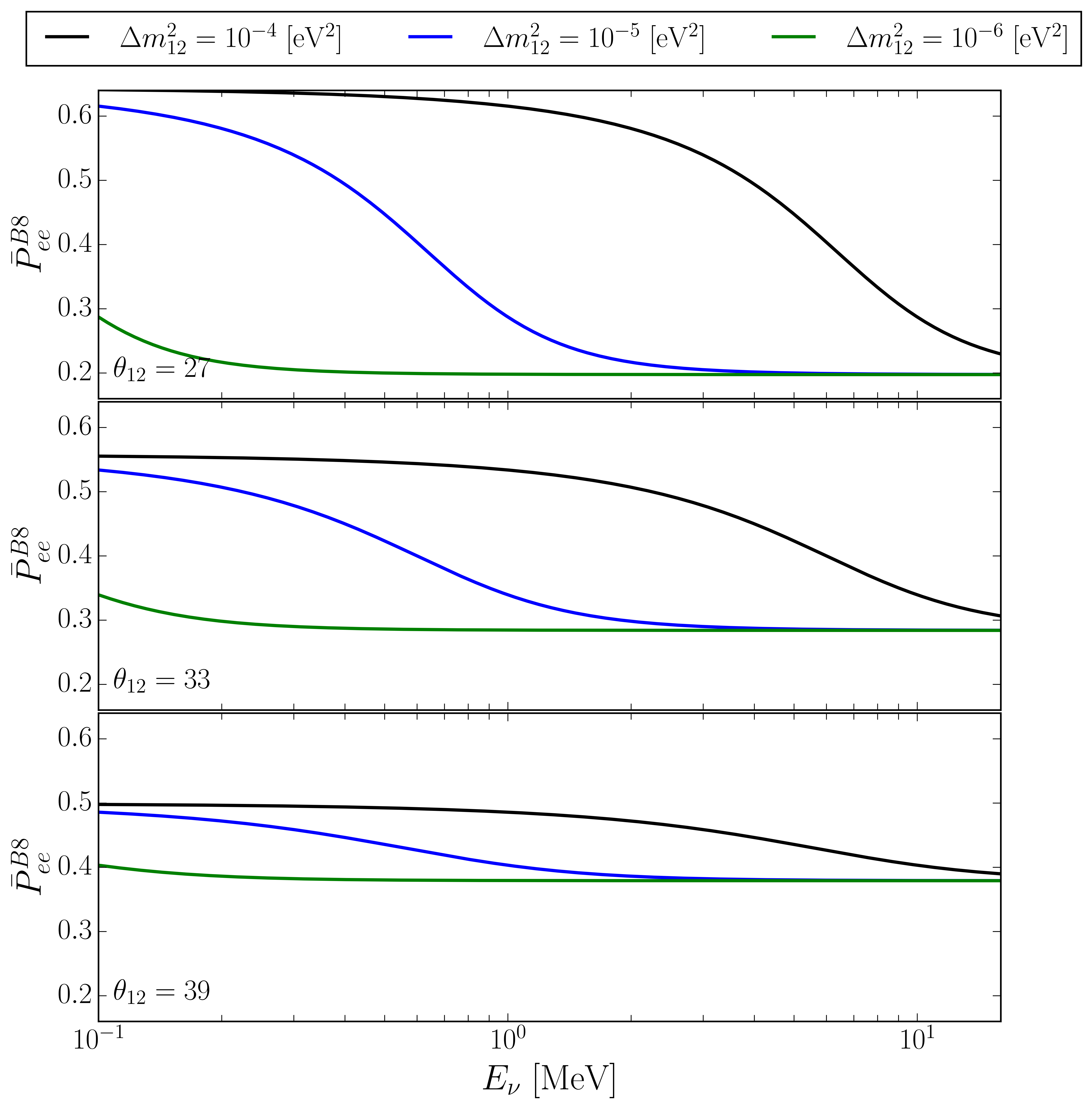
**Mixing angle $\theta_{12}$ and the mass splitting $\Delta m^2_{12}$ are two important relevant parameters**

**MSW standard effet**

$$\cos 2\theta_{12}^M = \frac{\cos 2\theta_{12} - V\frac{E_\nu}{\Delta m_{12}^2}}{\sqrt{(\cos 2\theta_{12} - V\frac{E_\nu}{\Delta m_{12}^2})^2 + \sin^2 2\theta_{12}}}$$

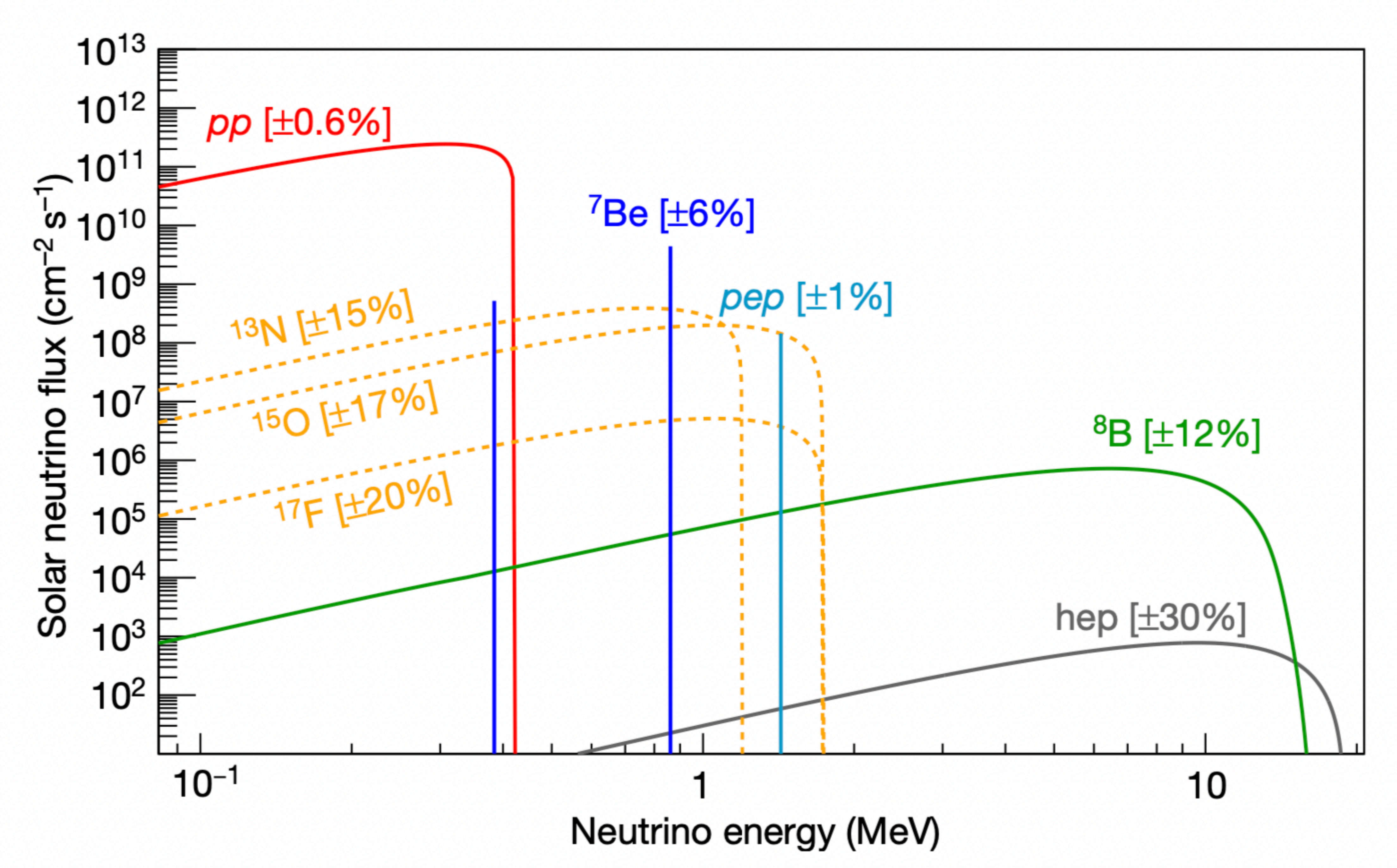
$$V \equiv 2\sqrt{2}G_F N_e(r)\,|_{\text{at production}}$$

$$P(\nu_e \to \nu_e) = \cos^4\theta_{13}\left(\cos^2\theta_{12}\cos^2\theta_{12}^M + \sin^2\theta_{12}\sin^2\theta_{12}^M\right) + \sin^4\theta_{13}$$

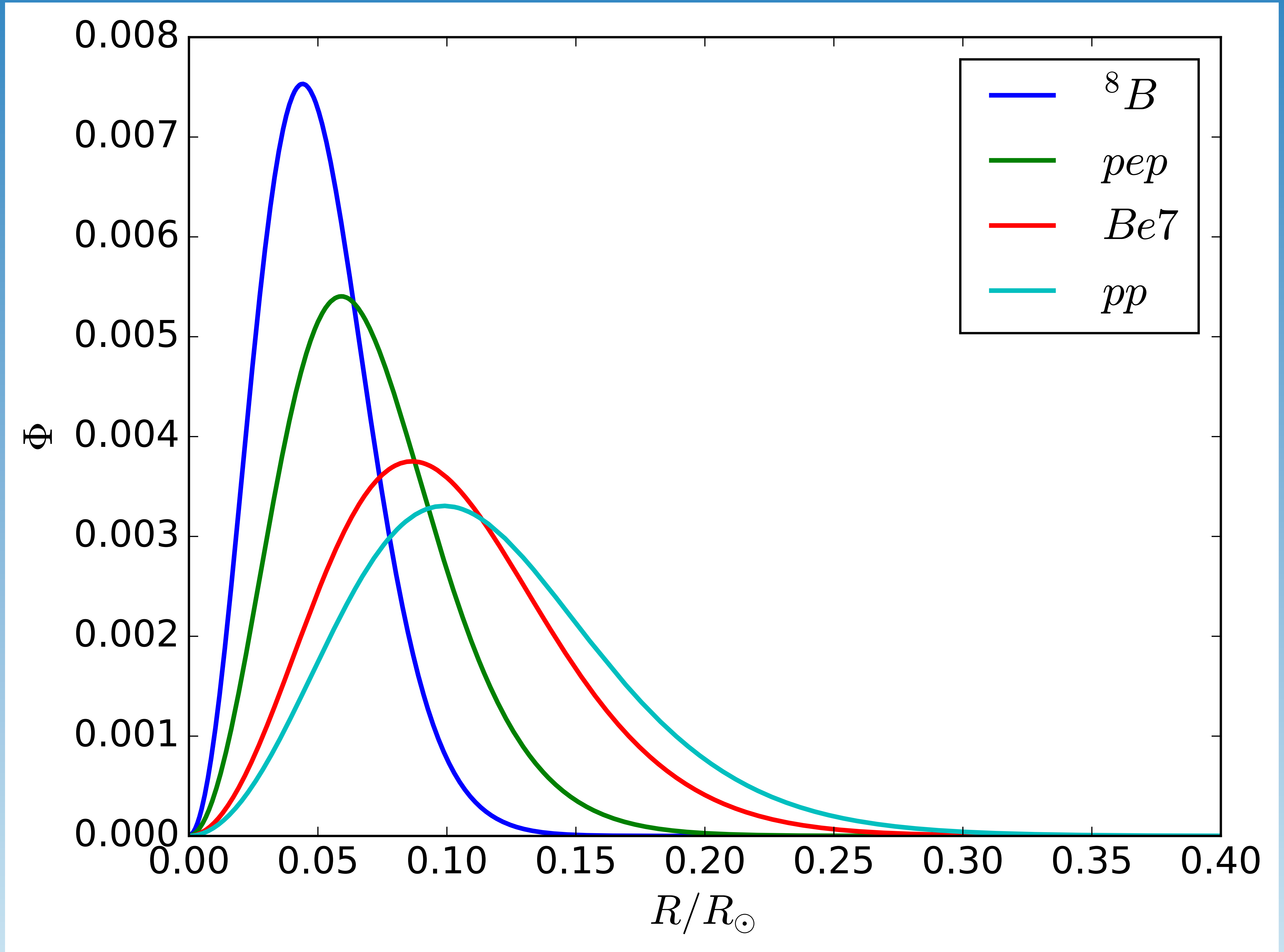


# Solar Neutrino Oscillations

$$\bar{P}^j_{ee}(E_\nu, L) \equiv \int_{R_\odot} P^j_{ee}\left(E_\nu, L, N_e(r)\right) \Phi^j(r)dr$$



"Comprehensive measurement of pp-chain solar neutrinos." *Nature* 562, no. 7728 (2018): 505-510.



http://www.sns.ias.edu/~jnb/

# The pseudo-Dirac scenario

Neutrino states can have both Dirac mass ($m$) and Majorana mass ($\mu$) terms

$$\bar{\Psi} m \Psi + \bar{\Psi}^c \mu \Psi \qquad \begin{pmatrix} 0 & m \\ m & \mu \end{pmatrix}$$

In general $m$ and $\mu$ are $3 \times 3$ matrices. We assume that both can be diagonalized in mass basis simultaneously

The energy-momentum eigenstates takes the form below

$$(E^2 - p^2)\begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} = \begin{pmatrix} m^2 & m\mu \\ m\mu & m^2 + \mu^2 \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}$$

# The pseudo-Dirac scenario

$$\begin{pmatrix} \frac{1}{2}\left[\mu + \sqrt{4m^2 + \mu^2}\right] & 0 \\ 0 & \frac{1}{2}\left[\mu - \sqrt{4m^2 + \mu^2}\right] \end{pmatrix}$$

$$\frac{2m}{\mu} \gg 1 \quad or \quad \frac{2m}{\mu} \ll 1$$

**In the limit $\mu \ll m$ we are in the regime of maximally mixing**

**Two Majorana mass states**

$$m \pm \frac{1}{2} m\mu$$

**Active Neutrino can oscillate to sterile neutrino**

$$p(\nu_L \to \nu_s) = \sin^2\left(\frac{m\mu}{2E_\nu} L\right)$$

# The pseudo-Dirac scenario

**Adding matter effect for the sun**

$$(E^2 - p^2)\begin{pmatrix}\nu_L \\ \nu_R^c\end{pmatrix} = \left[\begin{pmatrix}2pV & 0 \\ 0 & 0\end{pmatrix} + \begin{pmatrix}m^2 & m\mu \\ m\mu & m^2+\mu^2\end{pmatrix}\right]\begin{pmatrix}\nu_L \\ \nu_R^c\end{pmatrix}$$

**Inside the sun the mixing between active and sterile neutrino will be suppressed**

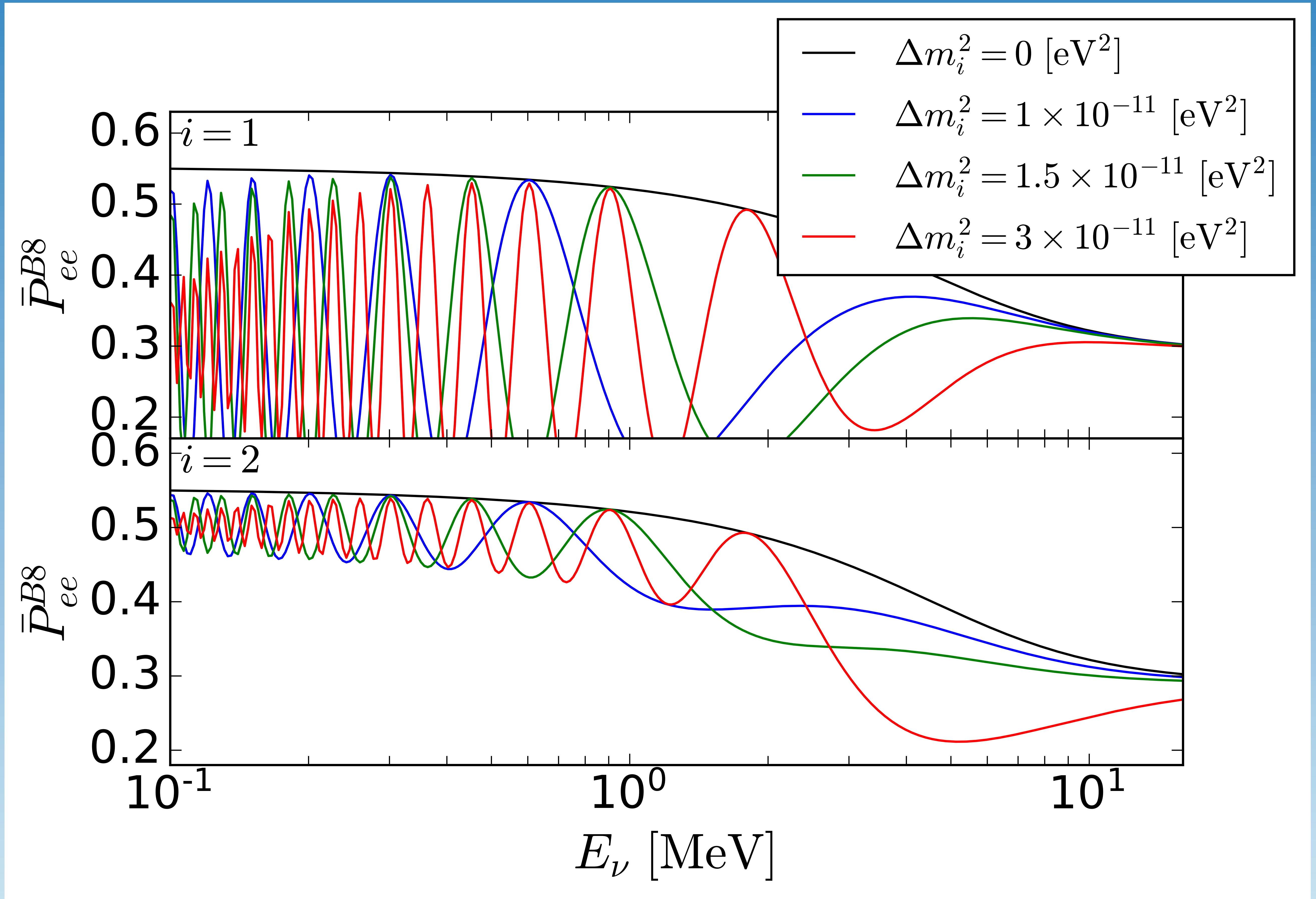
$$2pV \gg m\mu$$

**Therefore the standard MSW effect is working inside the sun**

**At the sun's surface we have an incoherent combination of active neutrinos**

$$P(\nu_e \to \nu_e) = \cos^4\theta_{13}\left(\cos^2\theta_{12}\cos^2\theta_{12}^M\cos^2(\frac{\mu_1 m_1 L}{2E_\nu}) + \sin^2\theta_{12}\sin^2\theta_{12}^M\cos^2(\frac{\mu_2 m_2 L}{2E_\nu})\right) + \sin^4\theta_{13}\cos^2(\frac{\mu_3 m_3 L}{2E_\nu})$$

# The pseudo-Dirac scenario



**In the following, I only keep one Majorana mass state at each step of our analysis**

$$\Delta m^2 \equiv 2m\mu \sim 4E_\nu L \sim 10^{-12}\ \mathrm{eV}^2$$

**The model is safe with respect to constraints coming from the early universe number of degrees of freedom**

# The pseudo-Dirac scenario

It seems the Solar Neutrinos have a slight preference for a non zero mass splitting

G Anamiati, RM Fonseca, M Hirsch, PHYSICAL REVIEW D 97, 095008 (2018)

The latest constraint is $\Delta m^2 \leq 1.1 \times 10^{-18} \mathrm{eV}^2$ by the observation of NGC 1068

Mild preference for $\Delta m^2 \sim 6 \times 10^{-20}\ \mathrm{eV}^2$

Rink Thomas, and Manibrata Sen. "Constraints on pseudo-Dirac neutrinos using high-energy neutrinos from NGC 1068." arXiv preprint arXiv:2211.16520 (2022).

Martinez-Soler, Ivan, Yuber F. Perez-Gonzalez, and Manibrata Sen. "Signs of pseudo-Dirac neutrinos in SN1987A data." Physical Review D 105.9 (2022): 095019.

There are also Ultra High Cosmic Neutrinos that are sensitive to $\Delta m^2 \sim 10^{-18} \mathrm{eV}^2$

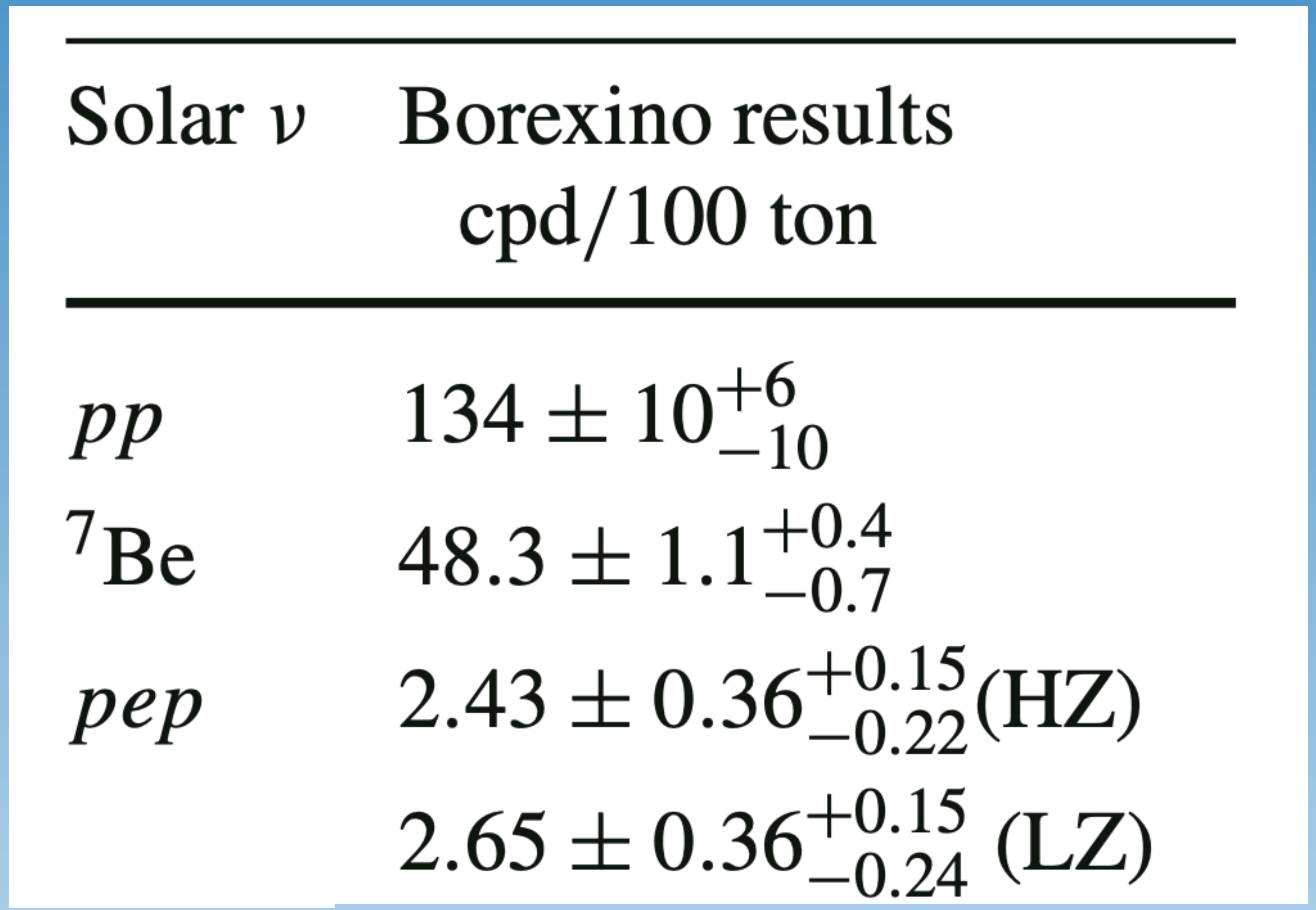
Arman Esmaili and Yasaman Farzan, JCAP12(2012)014

Future experiments such as DUNE and JUNO will explore the region $\Delta m^2 \sim 10^{-5} \mathrm{eV}^2$

G Anamiati, V De Romeri, M Hirsch, CA Ternes, M Tórtola, PHYSICAL REVIEW D 100, 035032 (2019)

# Data and Constraints

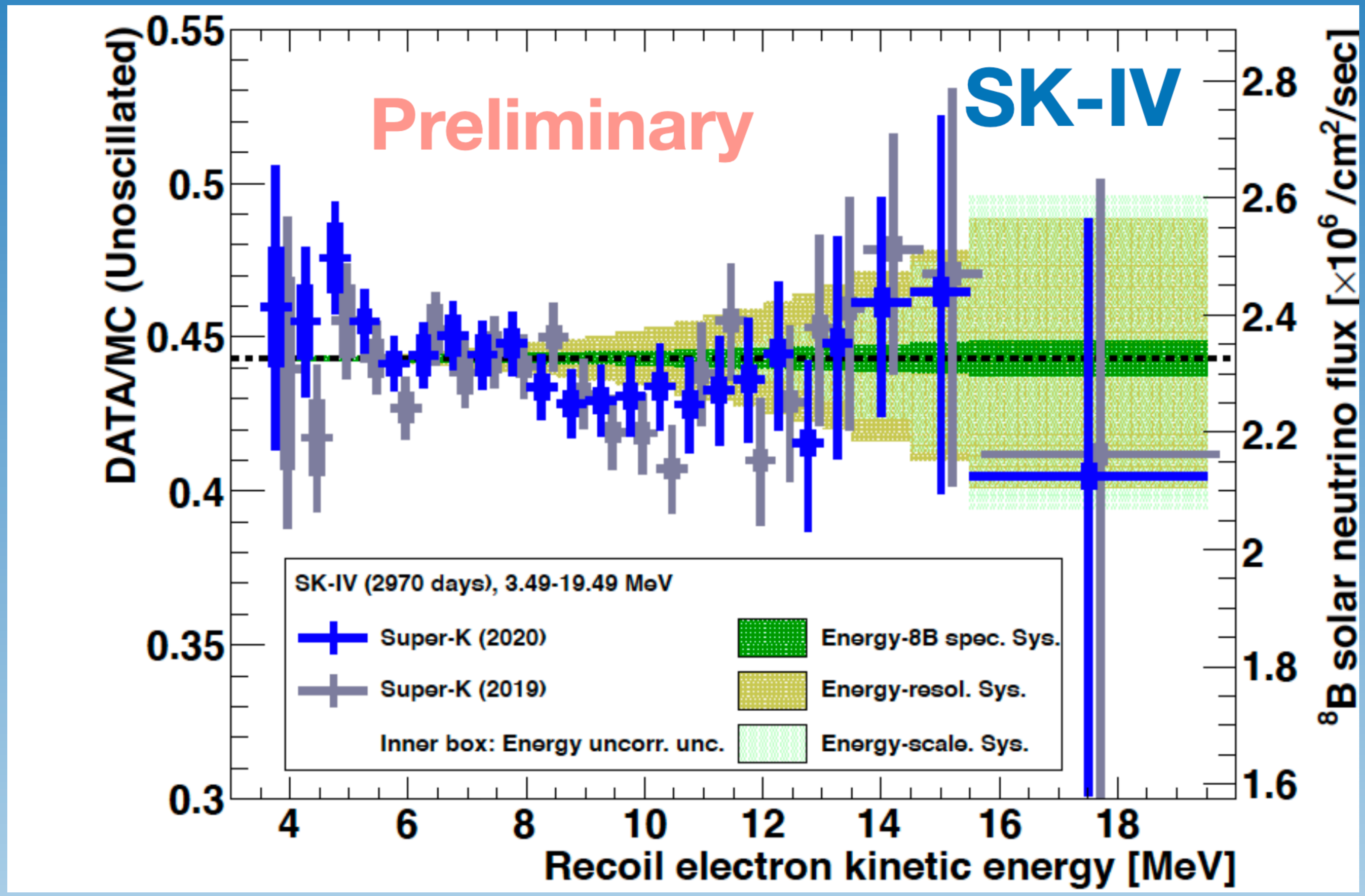
## BOREXINO



| Solar $\nu$ | Borexino results cpd/100 ton |
|---|---|
| *pp* | $134 \pm 10^{+6}_{-10}$ |
| $^7$Be | $48.3 \pm 1.1^{+0.4}_{-0.7}$ |
| *pep* | $2.43 \pm 0.36^{+0.15}_{-0.22}$ (HZ) |
| | $2.65 \pm 0.36^{+0.15}_{-0.24}$ (LZ) |

Agostini, M., et al. "Sensitivity to neutrinos from the solar CNO cycle in Borexino." *The European Physical Journal C* 80.11 (2020): 1-15

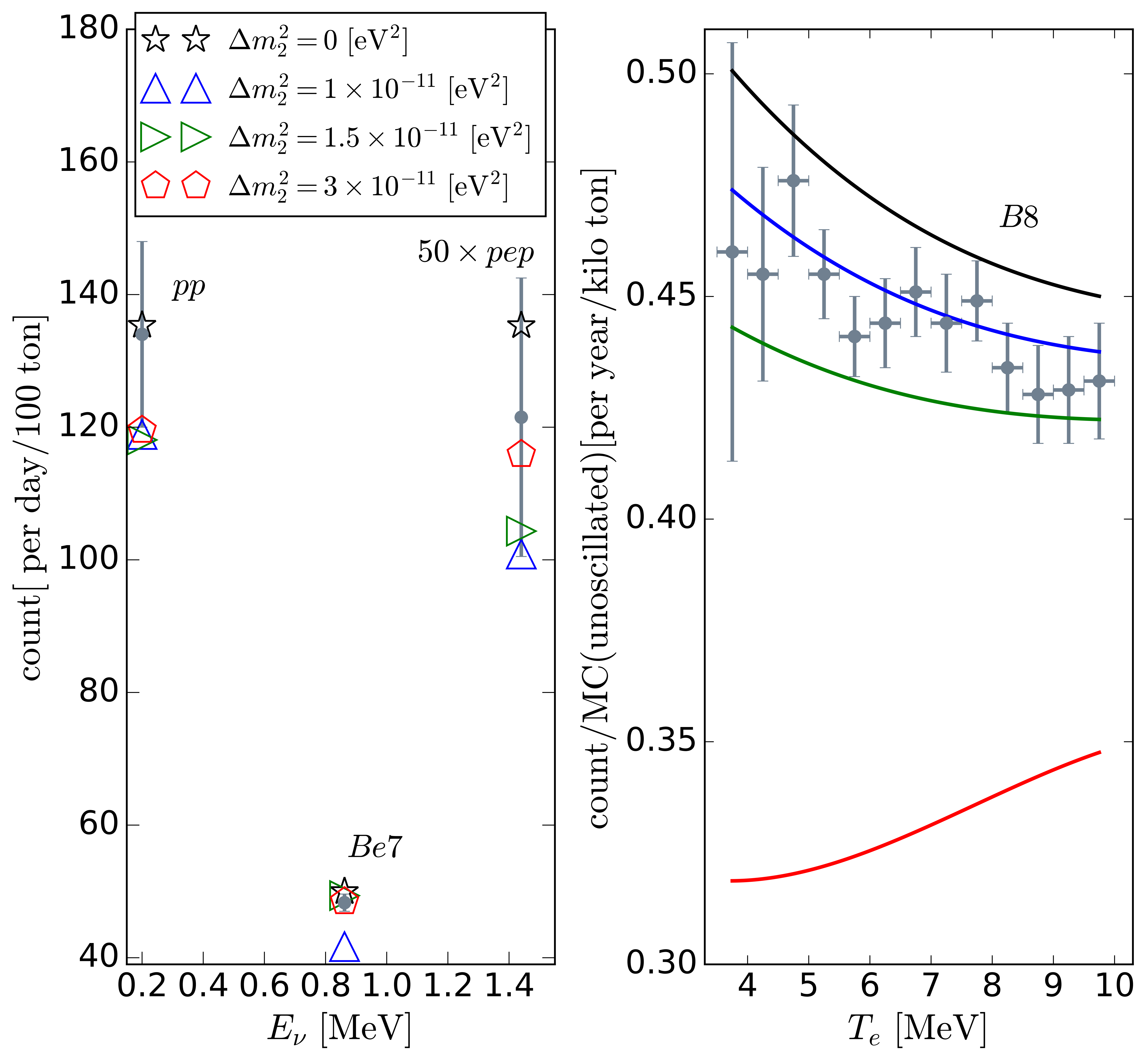
## Super-Kamiokande (2020)



Y. Nakajima (Super-Kamiokande Collaboration), Talk Given at the XXIX International Conference on Neutrino Physics and Astrophysics June 30 (2020), https://indico.fnal.gov/event/43209/contributions/187863/attachments/129474/ 159089/nakajima_Neutrino2020.pdf.

$$\mathscr{T}^j(t,\Delta t) = N\frac{t}{\Delta \mathrm{t}}\int_{\Delta \mathrm{t}} dt \int dT_e \int_{E_\nu(T_e)} dE_\nu\, \phi^j \frac{d\lambda^j}{dE_\nu}\left[\frac{d\sigma_e}{dT_e}P_{ee} + \frac{d\sigma_\mu}{dT_e}(1-P_{ee}-P_{es})\right]$$

# Data and Constraints



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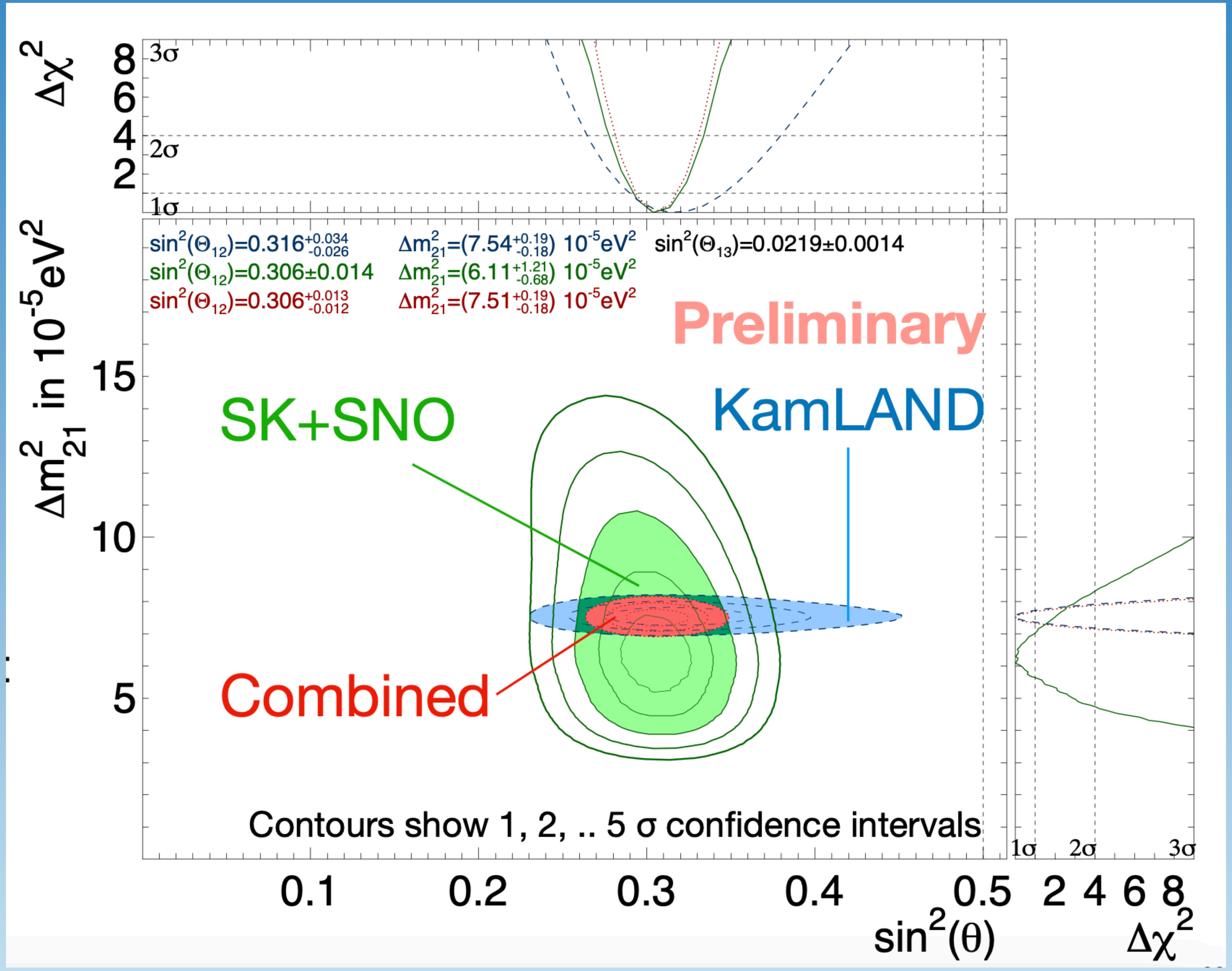
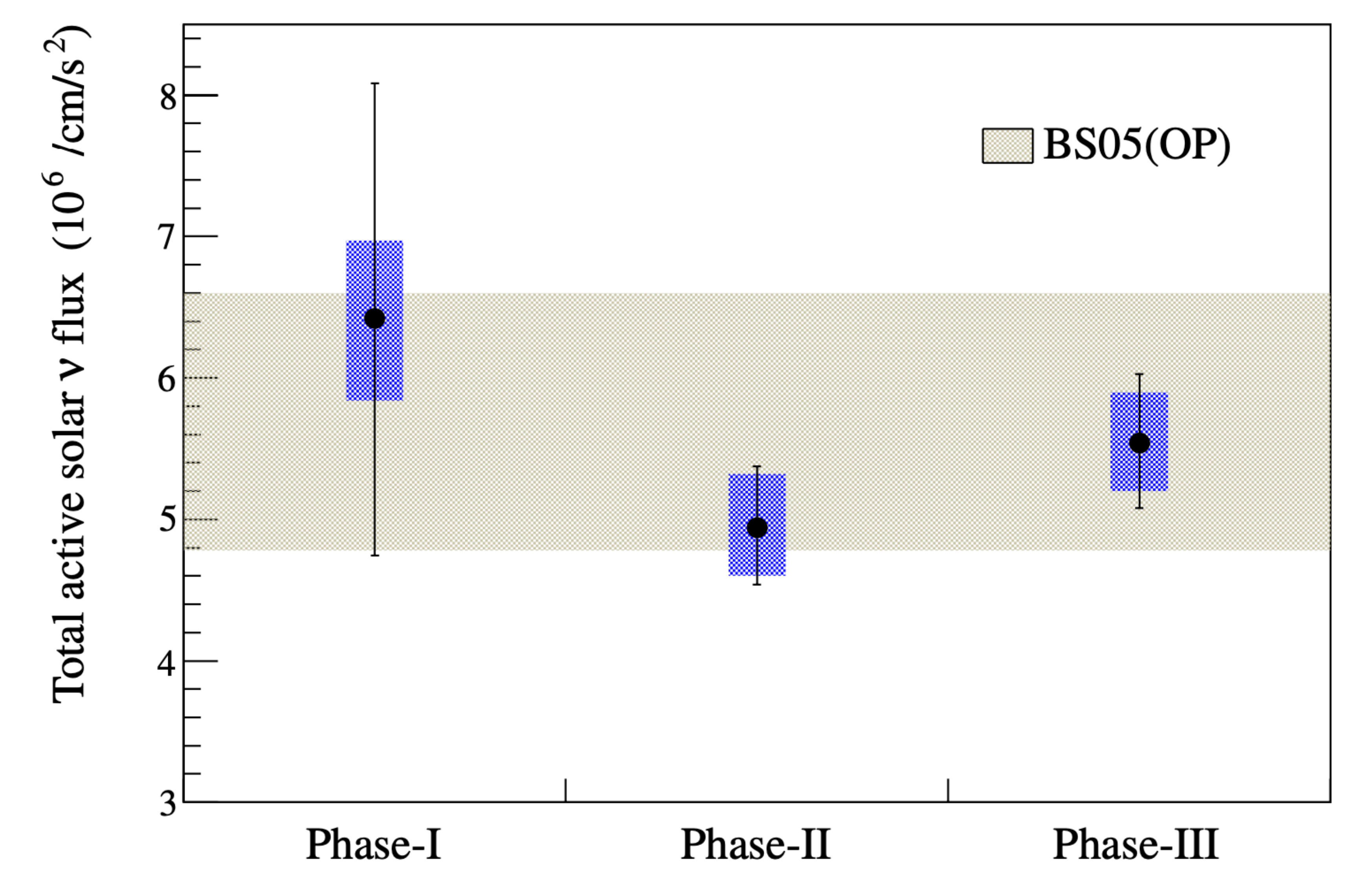


Y. Nakajima (Super-Kamiokande Collaboration), Talk Given at the XXIX International Conference on Neutrino Physics and Astrophysics June 30 (2020), https://indico.fnal.gov/event/43209/contributions/187863/attachments/129474/ 159089/nakajima_Neutrino2020.pdf.

$$\textbf{KamLAND}: \Delta m^2_{12} \sim (7.5 \pm 0.5) \times 10^{-5}\mathrm{eV}^2$$

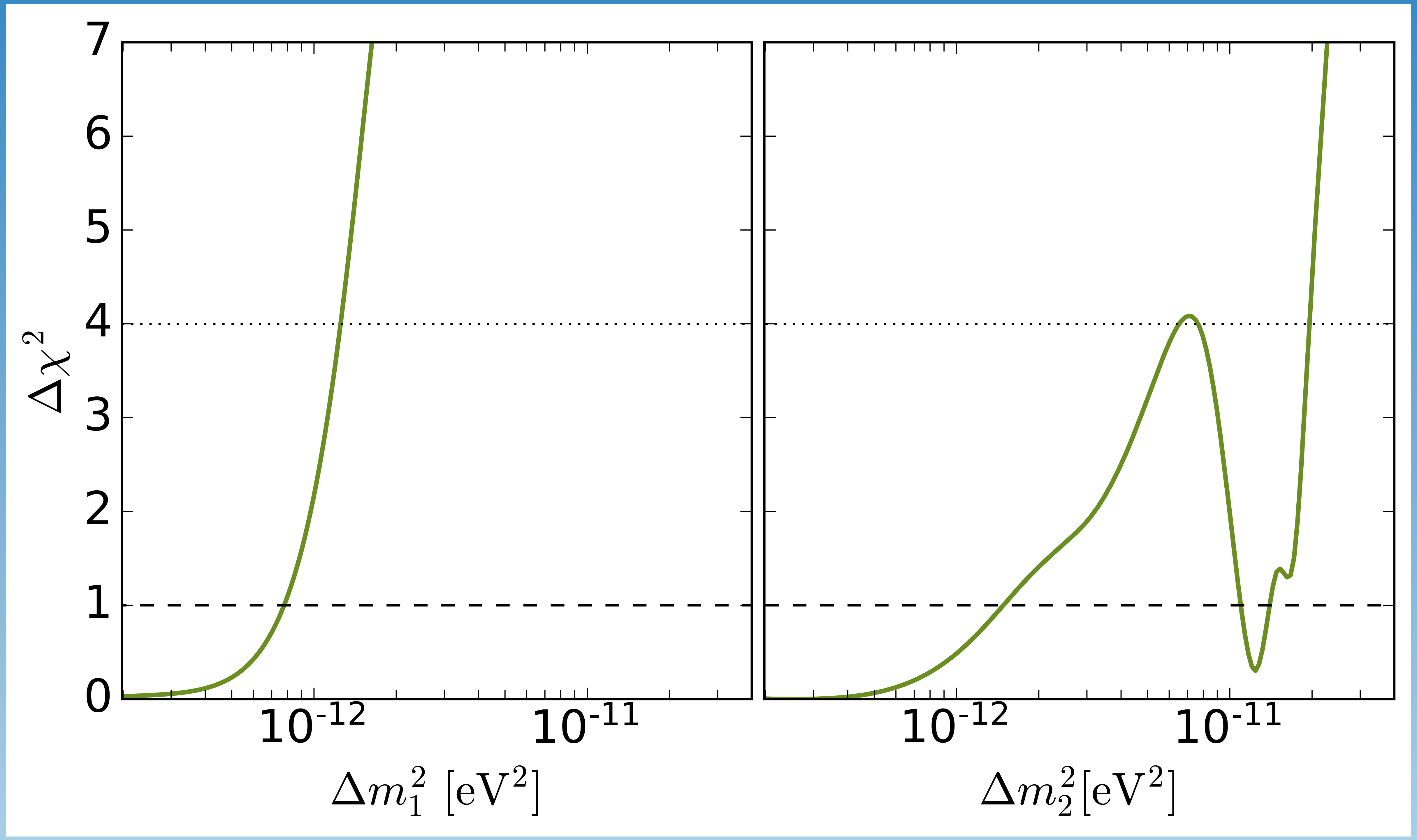


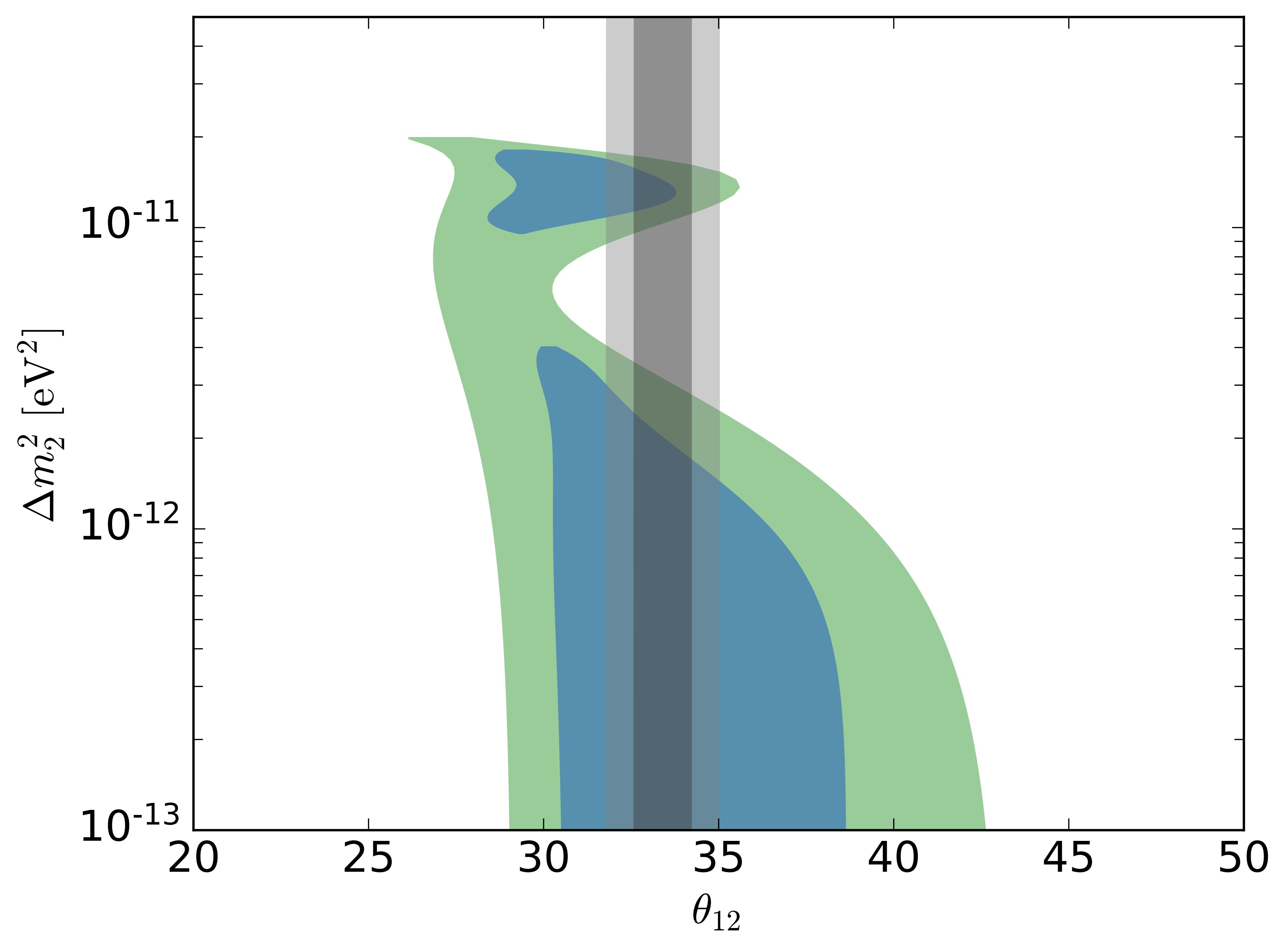
Bellerive, Alain, et al. "The sudbury neutrino observatory." *Nuclear Physics B* 908 (2016): 30-51

**From SNO results the sterile Neutrinos should contributes less than 10% of the total flux**

$$\frac{\Delta m^2 L_{\mathrm{kam}}}{2E_\nu} \ll 1$$

# Results

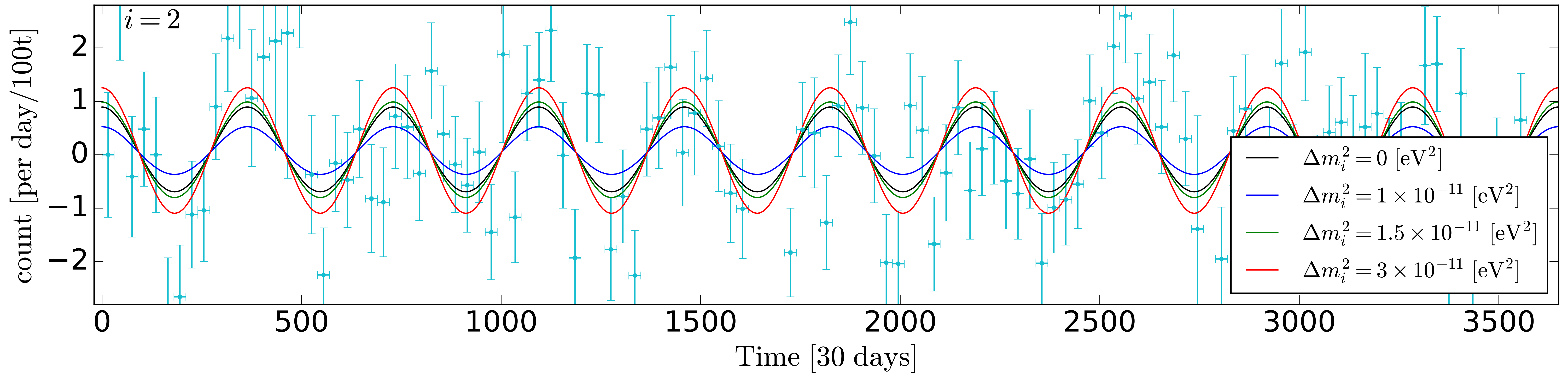




S.A, Yasaman Farzan "Revisiting pseudo-Dirac neutrino scenario after recent solar neutrino data." *Physical Review D* 107.7 (2023): 075029.

$$\chi^2_{min}(\Delta m_i^2, \theta_{12}) = \min_{\text{nusiance}} \left[ \chi^2_{Su} + \chi^2_{Bo} + \left( \frac{\Delta m^2_{21} - \Delta \bar{m}^2_{21}}{\sigma_{\Delta m^2_{21}}} \right)^2 \right]$$

# Seasonal Variation Amplitude

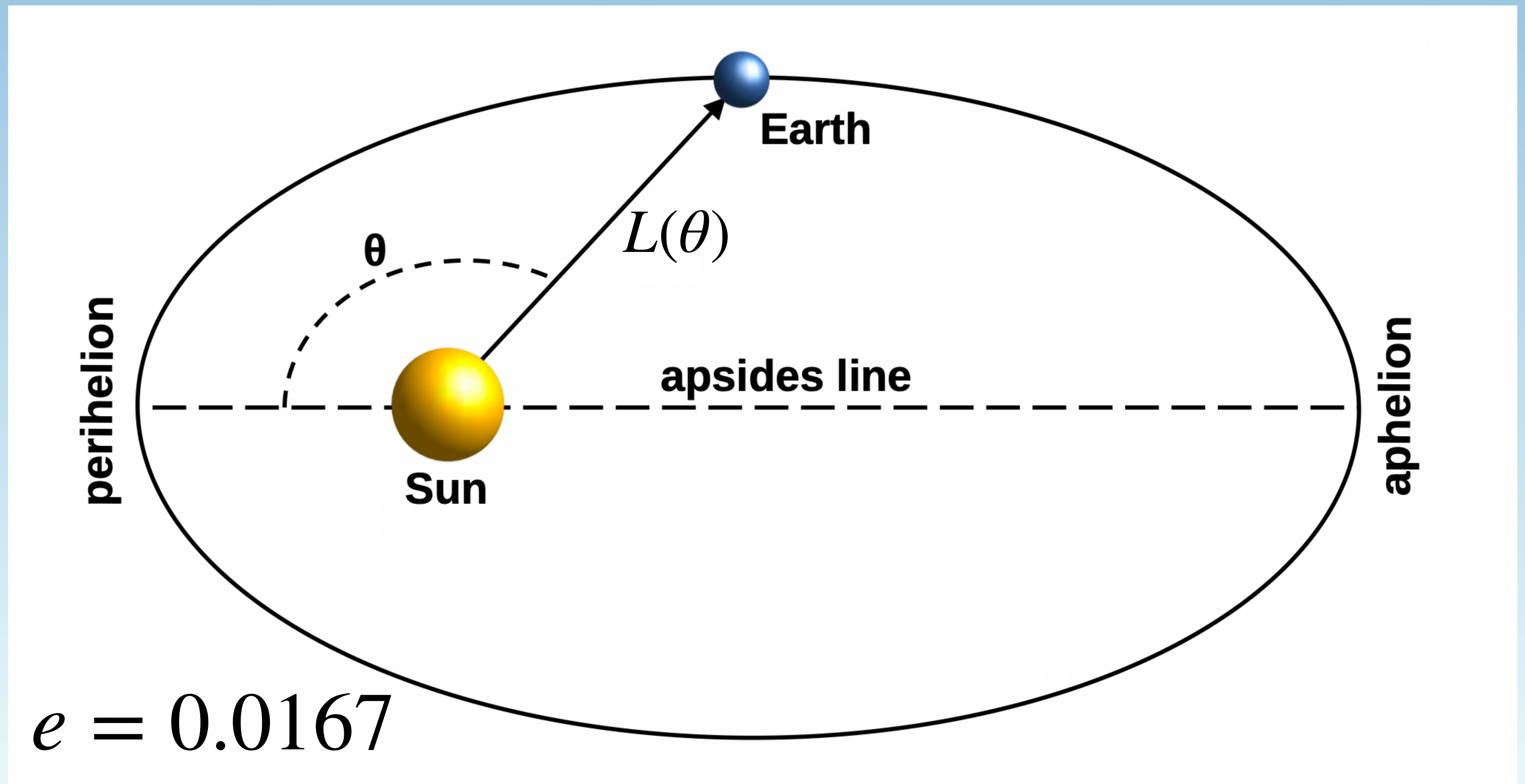


Appel, S., et al. "Independent determination of the Earth's orbital parameters with solar neutrinos in Borexino." *Astroparticle Physics* 145 (2023): 102778.

$$\mathscr{T} = N\int_{\text{bin}} dt \int dT_e \int_{E_\nu(T_e)} dE_\nu \; \phi \frac{d\lambda}{dE_\nu}\left[\frac{d\sigma_e}{dT_e}P_{ee} + \frac{d\sigma_\mu}{dT_e}(1 - P_{ee} - P_{es})\right]$$

$$L(\theta) = \frac{a(1-e^2)}{1 + e\cos\theta}$$

$$\mathscr{T}(L) = \bar{\phi}_\nu \frac{a^2}{L^2} F_\nu(L)$$



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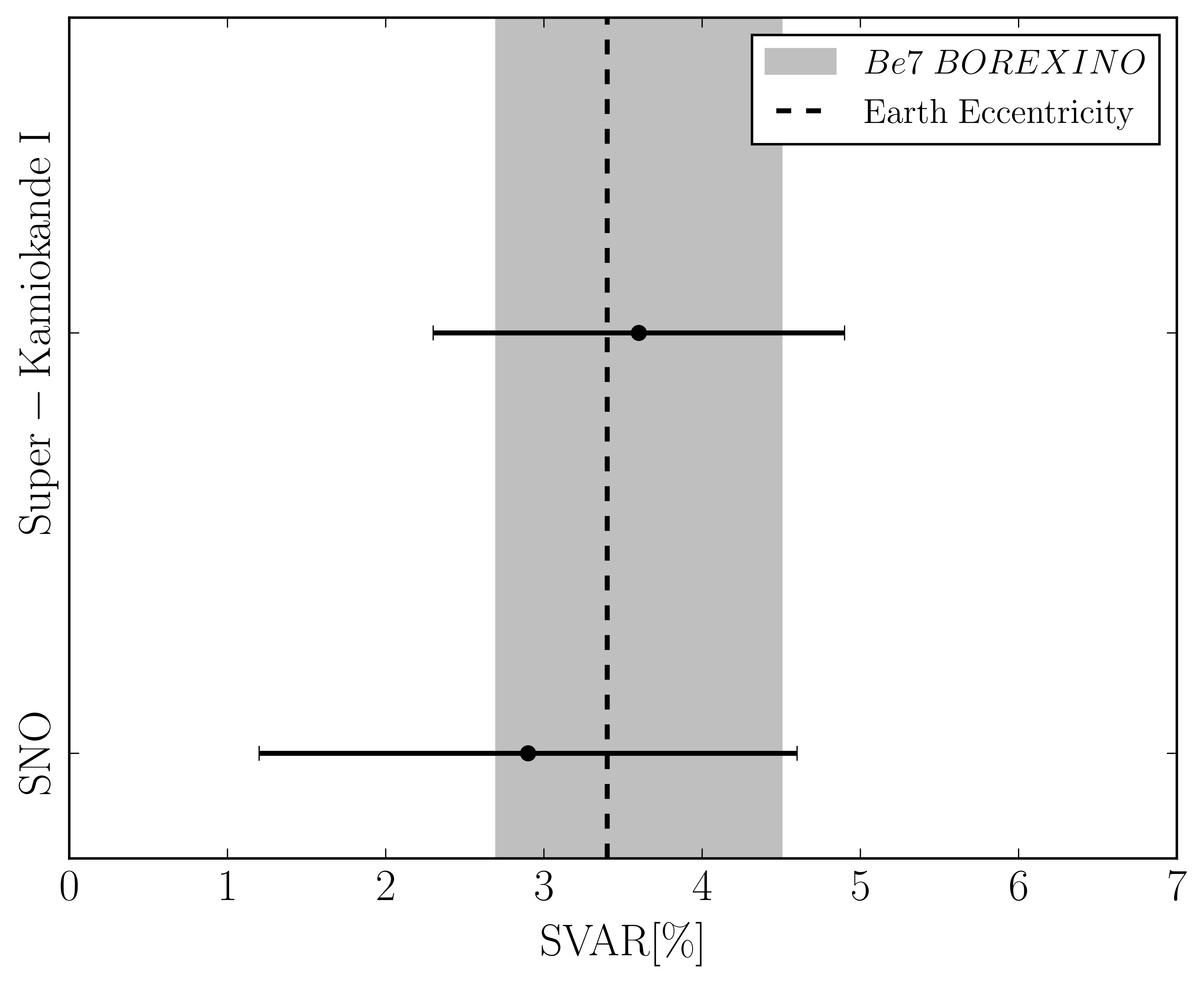
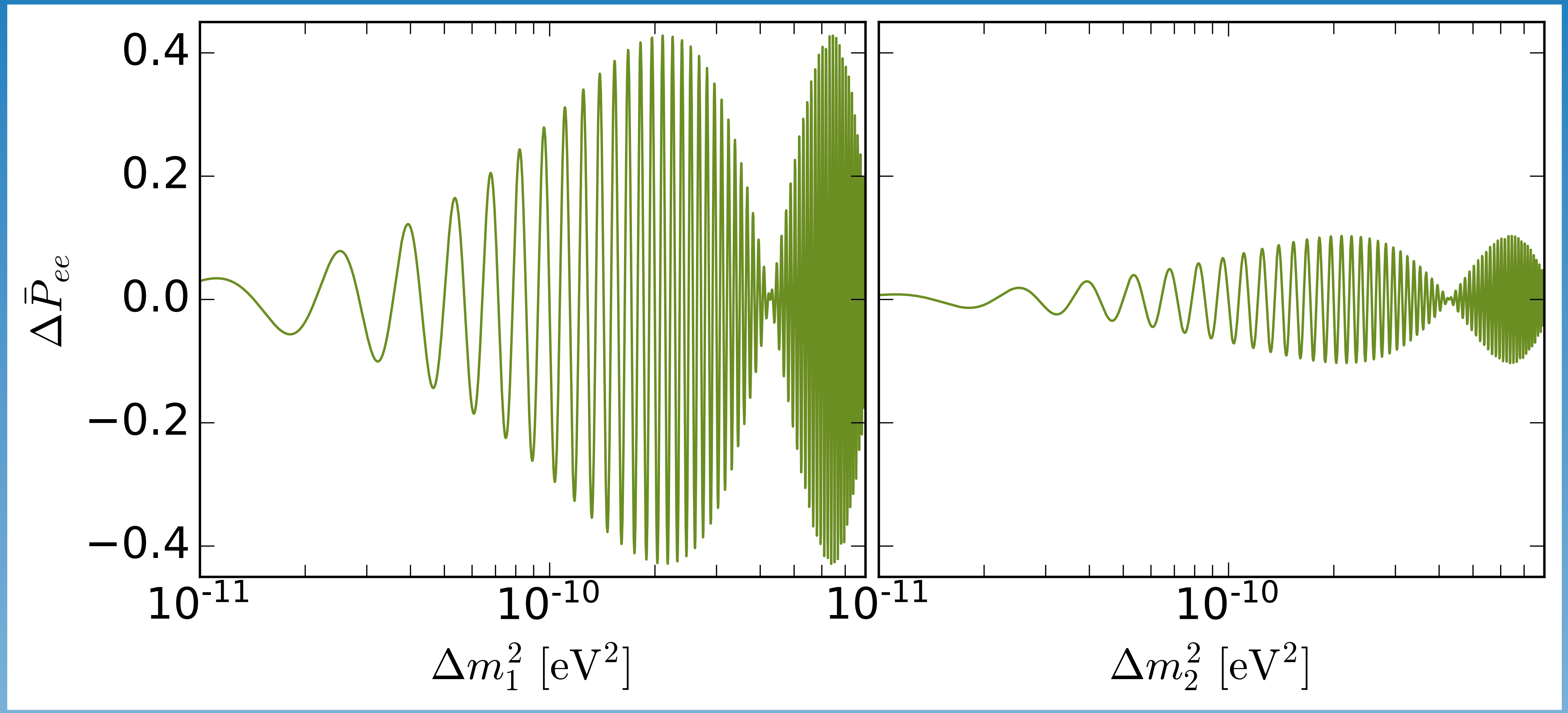
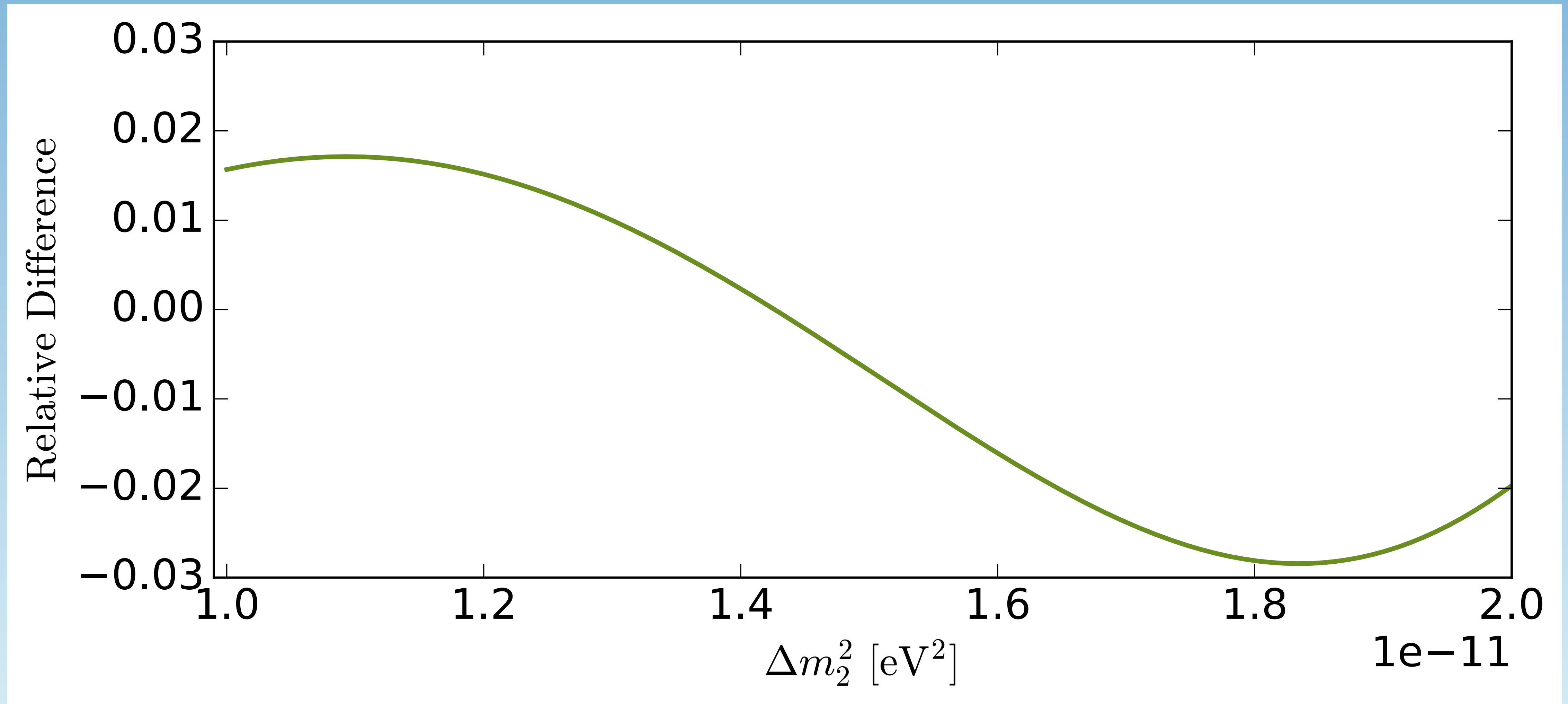
# Seasonal Variation Amplitude



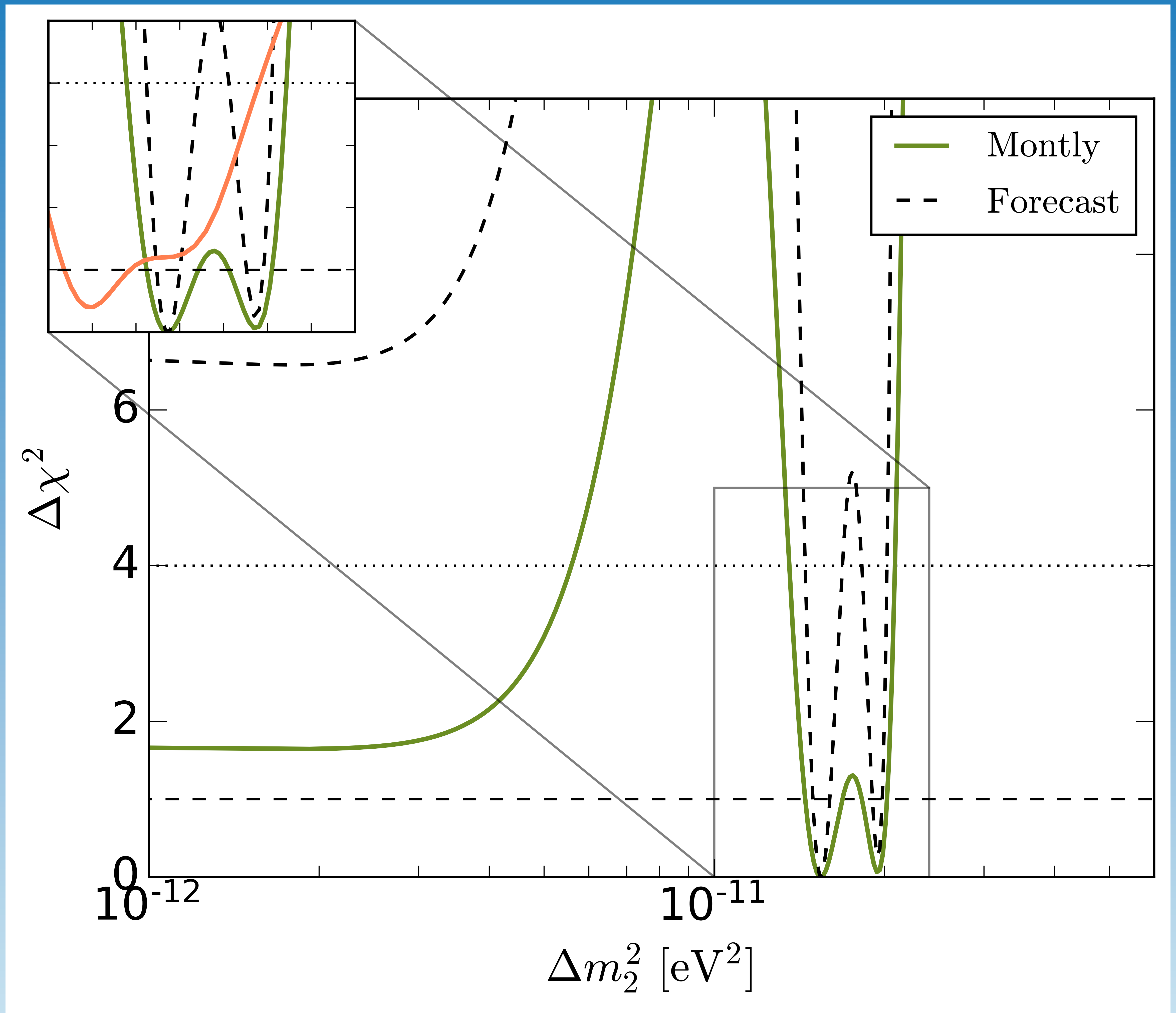




$$\Delta\bar{P}_{ee} = \bar{P}_{ee}^{Be7}(E_\nu, L_{max}) - \bar{P}_{ee}^{Be7}(E_\nu, L_{min})$$

# Results

$$\chi^2 = \sum_t \frac{\left[D_t^{Be} - \left(\mathscr{T}_t^{Be7}(\mathrm{day}, \mathrm{m}) - \mathscr{T}_t^{Be7}(\mathrm{day}, \mathrm{y})\right)\right]^2}{\sigma_t^2}$$



S.A, Yasaman Farzan "Revisiting pseudo-Dirac neutrino scenario after recent solar neutrino data." *Physical Review D* 107.7 (2023): 075029.

# Conclusion

We study the pseudo-Dirac scenario and put constraints on $\Delta m_1^2$ and $\Delta m_2^2$ with the latest BOREXINO and Super-Kamiokande results

The upper bound $\Delta m_1^2 < 1.5 \times 10^{-12} \mathrm{eV}^2$ and $\Delta m_2^2 < 2 \times 10^{-11} \mathrm{eV}^2$ have been found by yearly averaged data

Seasonal variation amplitude tend to a 5% more amplitude than the standard

There is a new solution in the range of $\Delta m_2^2 = (1.4 - 2) \times 10^{-11} \mathrm{eV}^2$ as well as the standard MSW solution that has been found by seasonal variation amplitude data

More precise data in the intermediate energies $E_\nu \sim (1 - 3)\ \mathrm{MeV}$ is required to test the new solution

# Is this a New Solution?